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Use of satellite pictures for the estimates of central pressure, maximum wind speed and the storm surge heights associated with tropical storms

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ABSTRACT. Using the available observations, we have derived an empirical relationship between maximum wind speed and the central pressure of the storms in the Bay of Bengal and Arabian Sea. The results obtained by this relationship are compared with the formulae available for Pacific and Atlantic storms and the satellite technique by Dvorak (1973). Utilising the nomograms given by Das (1973), we have also given a method to predict storm surge heights from satellite pictures for the storms crossing the north Bay of Bengal.

1. Introduction

The estimate of the Maximum Wind Speed (MWS) and Maximum Storm Surge (MSH) associated with tropical storms is a matter of considerable importance. Large elevations in sea level are known to cause much devastation and loss of life in coastal areas. Moreover, the primary meteorological element which determines the intensity of the storm, is the maximum wind speed associated with its cyclonic circulation. Direct measurements of MWS associated with a severe storm are generally not available, because anemometers often break or are blown away when a wind gust approaches hurricane speed. The ships, on experiencing strong winds, try to change their routes to avoid the main core of severe weather and strong winds. The severity of the storm is, therefore, generally judged on an estimated maximum wind speed. As the maximum wind speed and the maximum storm surge heights are closely associated with pressure deficiency in the storm centre, the estimates/observations of central pressure of the storm have been one of the main factors for determining the intensity of the storm.

Neglecting frictional effects, the cyclostrophic equation for obtaining the wind from pressure gradient is,

$$\rho v^2/r_t = \partial p/\partial r$$

where ρ is air density, v is wind speed, r_t is the radius of curvature of the trajectories, p refers to the pressure and r refers to the radial distance from the storm centre. As it is often difficult to draw isobars with sufficiently accurate spacing in the centre of a cyclone, it is not possible to compute the winds from the above equation.

Fletcher (1955) provided an empirical relationship for estimating maximum winds in tropical storms. This relies not upon the accuracy of pressure gradients, but on the storm's central and peripheral pressures. This relationship is expressed as :

$$V_{max} = 16\ (P_n - P_0)^{1/2}$$

where V_{max} is the maximum wind speed in knots, P_0 and P_n are the sea level pressures at the centre and the outer edge of the storm respectively. Based on additional aircraft reconnaissance reports, the National Hurricane Centre (NHC), USA, slightly modified the above relationship and expressed it as $V_{max} = 14\ (1013-P_0)^{1/2}$. For tropical storms in the western Pacific, the Joint Typhoon Warning Centre, Guam uses a relationship which varies with the latitude of the storm. According to it, the maximum wind speed of the tropical storm at 45° latitude will be nearly half of the value for the storm with the same sea level pressure at the centre of the storm, at 5° latitude. The pre-requisite for applying these relationships is the availability of the sea level pressure observation from the centre of the storm.

In recent years, satellite pictures have been widely utilised for estimating the MWS and the Minimum Sea Level Pressure (MSLP) of the tropical storms. Widger *et al.* (1965) gave nomogram to estimate central pressure of tropical storms from the size of the cirrus canopy observed in satellite pictures. The empirical technique by Timchalk *et al.* (1965) to estimate the MWS from the diameter of the dense overcast cloud mass, and the cloud pattern of the storm has been replaced by a T-number classification system given by Dvorak (1973). The system gives an empirical relationship to derive the MWS and also the central pressure from the Current Intensity (CI) number of the storm. This is assigned by taking into account factors like the cloud banding features, overcast cloud mass, outflow characteristics at the time of observation, and also the changes that have taken place in these characteristics after the previous observation. While Dvorak's technique gives only one relationship for estimating the MWS from CI number, it however, gives different values of central pressure for the storms in the Atlantic and Pacific — the central pressure for storms in Atlantic being higher by 6 mb compared to Pacific storms with the same CI number. No relationship between CI number and central pressure has been given by him for the storms in Indian Seas.

In this study we have made an attempt to find out the utility of different relations for estimating MWS and central pressure for cyclones in the Indian Seas. Using the techniue of Das (1973) for MSH we have also given an empirical relationship for predicting MSH from the CI number obtained from satellite pictures for storms crossing the north Bay of Bengal.

2. Estimates of maximun wind speed

The formulae given by Fletcher (1955) and later modified by NHC, USA is,

$$V_{\max} = K\,(P_n - P_0)^{1/2} \qquad (1)$$

where K is a constant, the value of which is given as 16 by Fletcher. The formula of NHC substitutes K by 14 and uses 1013 mb as P_n, the pressure of the outer edge of the storm. According to Srinivasan and Ramamurthi (1973) the outermost closed isobars of cyclonic storm in the Bay of Bengal and Arabian Sea has generally a value between 1005 and 1011 mb. Taking the mean value of 1008 mb as the pressure of the outer edge of the storms in the Indian Seas the formula becomes

$$V_{\max} = K\,(1008 - P_0)^{1/2} \qquad (2)$$

To obtain the value of K we compiled all available reports of minimum sea level pressure associated with storms in the Bay of Bengal and Arabian Sea from published papers, reports and the records of the India Meteorologocial Department. The observations for which reliable maximum wind reports were available within six hours of the pressure observation from the centre of the storms were sorted out and are presented in Table 1. In case of reports of the central pressure of storm from the coastal/island stations where actual wind reports are not available, the maximum wind speeds estimated from the damage reports are included in the table. There were only 2 cases of reconnaissance reports giving MWS and derived central pressure. These are also included in the table. The constant K calculated from Eqn. (2) in each case is also given in the Table 1.

TABLE 1

Cyclone	Date	Lowest pressure recorded (mb)	Max. wind observation/ estimated (kt)	Value of constant K
Bay of Bengal 1-7 Nov 1891	2 Nov	956·7	97	13·5
	5 Nov	984·4	83	17·1
Masulipatnam 21-30 Oct 1949	28 Oct	976·9	74	13·3
Bay of Bengal 28-31 Oct 1960	31 Oct	966·8	108	16·8
Arabian Sea 20-29 May 1963	24 May	947	104	13·3
Bay of Bengal 19-24 Oct 1963	21 Oct	984·2	80	16·4
Arabian Sea 9-13 Jun 1964	12 Jun	969·5	73	11·8
Rameshwaram 17-24 Dec 1964	23 Dec	978	85	15·5
Madras 1-4 Nov 1966	3 Nov	961	114	16·6
Bay of Bengal 3-8 Nov 1969	7 Nov	975	93	16·1
Bay of Bengal 4-8 May 1971	7 May	999·3	40	13·5
Paradeep 26-31 Oct 1971	30 Oct	966	100	15·4
Gopal pur 20-25 Sep 1972	21 Sep	982·0	100	19·6
Paradeep 4-9 Nov 1973	9 Nov	989·7	68	15·9

It will be seen from the available observations given in Table 1 that except for two extreme values of 11·8 and 19·6, the constant K varied in the remaining cases within the range of 13-17. Substituting the mean value of K the MWS-pressure deficiency relationship for the storms in the Bay of Bengal and Arabian Sea can be written as—

$$V_{\max} = 15\,(1008 - P_0)^{1/2} \qquad (3)$$

The MWS curve obtained from the above formula is shown in Fig. 1 along with the MWS curve obtained from NHC formula. It will be seen that the two curves run very close to each other thus suggesting that the modified version of the Fletcher's formula (Eqn. 1) can be utilised for storms in Indian Seas, with the same degree of accuracy as the NHC formula for the storms in west Atlantic and east Pacific.

According to this formula the cyclonic storms and severe cyclonic storms in the Bay of Bengal and Arabian Sea will have a pressure deficiency of 6-10 mb and 11-18 mb respectively.

As we have stated earlier, the value of K in most cases varied from 13 to 17. By taking the mean value of 15 the error involved will be of the order of $\pm$ 8 kt and $\pm$16 kt only for pressure deficiencies of 16 and 64 mb respectively.

3. Central pressure from satellite pictures

Dvorak's method for estimating central pressure from CI number gives MSLP of 1010 and 1004 mb for the lowest CI value of 1·5 for disturbances in the Atlantic and the Pacific. The central pressure for Atlantic is thus higher than the mean pressure (1008 mb) at the outer edge of disturbances in the Indian Seas. We have, therefore, preferred to compare the available values of central pressure for the storms in the Bay of Bengal with those obtained by Dvorak's technique for Pacific storms. The results are given in Table 2.

It can be concluded from the above that the central pressure given by Dvorak's method for Pacific storms can be also applied for the storms in the Indian Seas.

Dvorak's method gives a pressure deficiency of about 11-19 mb for cyclonic storms and 20-28 mb for severe cyclonic storms. These deficiencies are much closer to the values of 13-18 mb and > 18 mb for cyclonic and severe cyclonic storms considered by the India Meteorological Department, than the deficiency obtained from a modified version of Fletcher's formula.

A comparison of MWS derived by Dvorak's method and the empirical relationships given in Eqn. (3) shows that Dvorak's method gives lower estimates of MWS for the same value of pressure deficiency. The estimates, however, tend to be closer for storms of higher intensities.

4. Storm surge heights from satellite pictures

Das (1973) prepared nomograms for predicting the maximum surge at the time of the storm crossing the north Bay coast. The values obtained from these nomograms are based on pressure deficiency in the storm centre and the speed of the storm at the time of crossing the coast. For the speed of the storms we have assumed an average speed of 15 km per hour. This has been obtained from the frequency of speeds of 130 storms/depressions which crossed the north coast of the Bay of Bengal in the pre-monsoon and post-monsoon months during the years 1891-1960, as given in the Atlas of *Tracks of the storms/depressions in the Bay of Bengal and Arabian Sea* published by the India Meteorological Department (1964). In the relationship given in Table 3 the pressure deficiency obtained from the Dvorak's method for Pacific storms is considered true for storms in the north Bay.

The values given in Table 3 are to be added to the normal tide height at the time of crossing the coast obtained from the tide tables. As direct observations of the pressure from the centre of the storm are seldom available, the pressure deficiency in the storm centre can be estimated from the observations of the MWS. In the absence of either, the values of MSH can be predicted

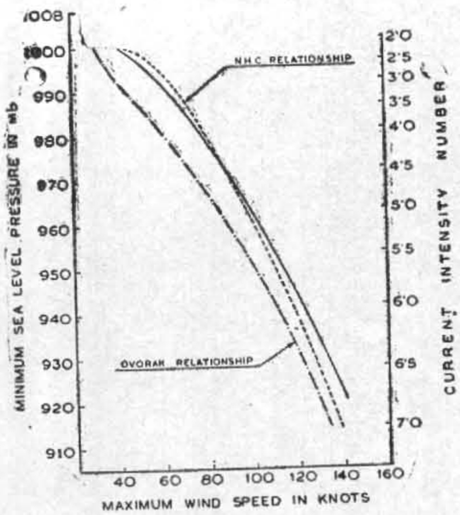

Fig. 1

TABLE 2

Cyclone	Date	CI No. from satellite pictures	Observed MSLP	Central pressure estimated†
Bay of Bengal 3-8 Nov 1969	7 Nov	5	975	964
Paradeep Oct 1971	30 Oct	5	966	964
Gopalpur Sep 1972	21 Sep	4	982	982
Paradeep 4-8 Nov 1973	5 Nov	4	981·5	982
Bangla Desh 7-12 Nov 1970	11 Nov	6·5	964*	928

†By Dvorak technique for Pacific storms

*Lowest pressure reported by the sinking ship *Mahajagmitra* on 11 November 1970 when it was close to the storm centre and was experiencing strong winds. Central pressure of the storm was obviously much lower than the reported value.

TABLE 3

CI No.	MSH values in metres for storms crossing coast near		
	Paradeep	Saugar Island	Chittagong
4 or less	<1·5	<1	<2·2
4·5	1·9	1·3	2·7
5	3·0	1·9	3·5
5·5	3·8	2·3	4·1
6 or more	>3·8	>2·3	>4·1

from the satellite pictures by the above relationship. We note, however, that the principle of superposing the estimated surge on the astronomical tide need not be strictly correct. The total sea level elevation would certainly also depend on the phase of the astronomical tide. This aspect has not been considered in the paper.

5. Discussions

The empirical relationship given in Eqn. (3) for storms in the Bay of Bengal and Indian Seas, gives results which are comparable to NHC formula for storms in west Atlantic and east Pacific. The relationship can be applied only after the system has attained the intensity of a severe cyclonic storm. The application of the relationship for less intense systems gives higher estimates of MWS. For example, according to the accepted convention in the India Meteorological Department, the cyclonic storms with MWS of 34-47 kt should have a pressure deficiency of 13-18 mb. The relationship gives these values of wind speeds for the pressure deficiency of 6-10 mb which is known to be associated with the depressions in the Indian Seas.

According to the method given by Dvorak, cyclonic storm intensity is reached with CI number of 2·5-3·5, which corresponds to a pressure deficiency of 11-21 mb and are very much closer to conventional values.

For the same values of central pressure the estimates of MWS by the two methods differ by 20 kt, in the early stages of storms. For mature storms, the difference in the estimates of winds by the two methods reduce to 10 kt only. This suggests that, while the Dvorak's method has an advantage over modified Fletcher's method in the developing stages, the two tend to give similar results for mature storms.

The central pressure values obtained by the two methods differ by about 10 mb for the same value of MWS. The values obtained by satellite pictures being lower than those obtained by the relationship given in Eqn. (3). As discussed, the former appears to be more close to the actual observations for storms in the Indian Seas.

In the absence of the direct observations of pressure from the centre of the storm, the relationship given for MSH from CI number will provide a valuable first guess for predicting storm surges.

Apart from giving an estimate of MWS, the satellite pictures provide valuable information about the isotach pattern associated with the MWS. According to Dvorak (1973) the 40 kt isotach normally encloses the outer limits of the central features of the storms, *e. g.*, overcast quasi-circular bands, the central dense overcast, and the eye with no central overcast. The dense overcast cumuliform bands curving into the main cloud system, if present, are usually enclosed within the 30 kt isotach.

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